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Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature

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ABSTRACT

Forest biomass is a renewable source that has the potential to substitute fossil fuels in many applications, from the generation of bioenergy (heat, electricity or transportation fuels) to the production of bioproducts (chemicals and other materials). The increased use of forest biomass could support the reduction of anthropogenic carbon emissions to the environment and could help forest-dependent communities achieve energy independence while generating jobs. The viability and feasibility of generating valuable products from forest biomass depend on ensuring the long-term availability of biomass supply with the required quality at a competitive cost. This calls for a cost-efficient design of the forest biomass supply chain. Social and environmental aspects have to be considered in the design as well to guarantee sustainable use of this renewable resource. In this paper, we present a review of studies that assessed or optimized economic, social and environmental aspects of forest biomass supply chains for the production of bioenergy and bioproducts. The majority of studies so far considered either economic (techno-economic and optimization studies) or environmental (life cycle assessment studies) aspects of bioenergy projects. Nevertheless, there is a recent trend to integrate economic, environmental and social aspects in the assessment and optimization of forest biomass supply chains. Combined approaches integrating multi-objective optimization and life cycle assessment have started to flourish. In these studies, GHG emissions are the most frequently used environmental indicator, production and capital costs are the preferred economic measures and the number of created jobs is the most considered social criterion. Further research has to be done to study and assess the potential social impacts of using forest biomass. There is a need for further development of decision support tools that consider economic, environmental and social criteria to aid the design and planning of forest biomass supply chains.

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1. Introduction

There is an increasing interest in intensifying the production and use of biomass to replace fossil fuels for the production of heat, electricity, transportation fuels [1], and various types of chemicals, plastics and other materials. International organizations, such as the International Energy Agency, encourage the use of biomass waste and residues for energy production because it can generate profit, contribute to the mitigation of greenhouse gas emissions, and help communities diversify their energy sources and achieve energy independency without threatening the world's food supply [2]. In some regions, there is an abundance of woody residues and solid wood waste (forest biomass) generated from forest management activities and forest products manufacturing. It is possible to generate valuable products from forest biomass that in many cases is disposed at landfills or is incinerated [3].

Despite the benefits of using forest biomass, technical and economic challenges hinder its intensified use. Forest residues are scattered over wide regions which increases the collection, handling and transportation costs. Moreover, there is variability in the amount and quality of forest biomass due to forest accessibility during a year, weather conditions, pre-processing, transportation and storage conditions, and competition from other end users [4]. In addition, forest biomass has lower energy density than a large number of competing fossil fuels [5]. These result in a costly and complex logistics of procuring, transporting and using forest biomass. Biomass logistic costs typically account for 20–40% of delivered fuel costs [6] and restrict the competitiveness of forest biomass against other energy sources. A cost efficient design of the forest biomass supply chain is critical to overcome these challenges.

In addition, the raising public awareness on sustainability issues requires decision makers to understand the life cycle impacts of forest biomass systems on the environment and society. Quantitative techniques can aid decision makers to understand the economic, environmental and social impacts of forest biomass supply chains. This understanding is required to mitigate undesirable impacts, increase the benefits associated with the use of forest biomass, and ensure the sustainability of new projects that attract community, government and investors' interest and support.

Previous studies reviewed the literature on modeling of biomass or bioenergy supply chains [3,7–13]. Key issues associated with the design, planning and management of bioenergy supply chains (from biomass harvesting to conversion) and biofuel supply chains (from biomass procurement to biofuel distribution) were discussed by Gold et al. [8], Mafakheri et al. [12] and Yue et al. [13]. Decisions addressed in the design and planning of biomass and bioenergy supply chains have been categorized by Iakovow et al. [7], Sharma et al. [9], and De Meyer et al. [14], with an emphasis on discussing the decision planning level (strategic, tactical and/or operational). Modeling approaches to support decision making in bioenergy supply chains were analyzed by Sharma et al. [9], De Meyer et al. [14], Shabani et al. [3] and Awudu and Zhang [11]. The latter two papers [3,11] also reviewed modeling approaches for incorporating uncertainty in optimization of biomass supply chains. Multi-criteria decision methods that have been applied to bioenergy systems were reviewed by Scot et al. [10]. Most of these papers only focused on the economic aspect of forest biomass supply chains, and those papers referring to social and environmental aspects only listed some related factors that are important to be considered in the design of bioenergy supply chains [7,8,10–13] without reviewing the relevant papers. Recently, a number of studies integrated economic, environmental and social factors in the assessment and optimization of forest biomass supply chains. Therefore, it is timely to review and discuss what has been done so far towards considering different sustainability aspects in the design and planning of forest biomass supply chains.

In this paper, we aim to present and discuss the modeling approaches used to assess and optimize economic, environmental and/or social criteria in the design and planning of forest biomass supply chains for the production of bioenergy (heat, power and transportation fuels) and other bioproducts (e.g. hydrogen). First, we explain technical, economic, environmental and social aspects relevant in the design of forest biomass supply chains. Then, we classify papers into techno-economic assessments; environmental life cycle assessments; integrated economic, social and environmental assessments; economic optimization models; and multi-objective optimization models. We discuss distinctive features and limitations of each approach, and provide some suggestions for further research.

2. Sustainability considerations in forest biomass supply chains

According to Lunnan et al. [15], sustainable use of forest biomass resources requires that all the benefits obtained from their current use do not compromise the ability of future generations to benefit from them in a similar manner. It is important to consider technical, economic, environmental and social issues in the design of forest biomass supply chains. Fig. 1 depicts a general structure of the forest biomass supply chain that is composed of five basic processes: biomass procurement, storage, transportation, pre-processing, and conversion [7]. Some studies added a sixth process corresponding to the distribution of the energy and bioproducts (e.g. [16,17]).

2.1. Technical and economic considerations

The conversion of forest biomass into bioenergy and bioproducts can generate additional revenue streams for the forest products sector and improve the economic viability of thinning and other forestry management operations [18]. For this to be feasible, technical and economic aspects of the whole supply chain are important and should be addressed when designing and planning new forest biomass utilization projects.

Some of the most important technical aspects in the design of production systems for bioenergy and bioproducts are the type, efficiency and scale of selected conversion technologies. The type of technology required for biomass conversion is based on the desired product and the available type of forest biomass. Biochemical and thermochemical technologies are the most suitable ones for converting lignocellulosic biomass (forest biomass

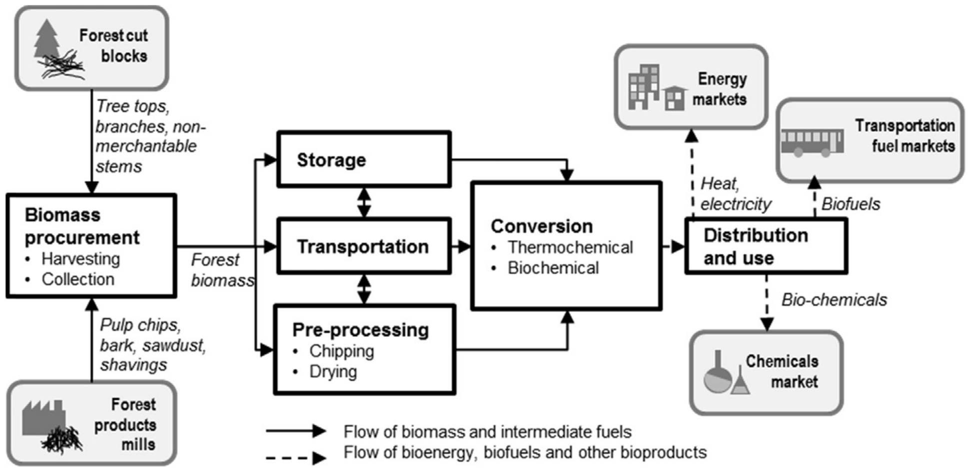

Fig. 1. General structure of a forest biomass supply chain.

included) into energy and chemicals [19]. Biochemical processes such as fermentation are used for the production of liquid or gaseous fuels [20]. Thermochemical processes such as combustion, gasification and pyrolysis are used for the production of fuels, heat and electricity [20]. The conversion efficiency of a technology determines the amount of product that can be obtained per unit of biomass input. Higher efficiencies represent lower operating costs, but they typically come with higher capital requirements [20]. The size of a conversion technology influences the economic feasibility of producing bioenergy and bioproducts. Since capital costs of conversion technologies are high, achieving economies of scale is important [21]. However, operating scales are technically restricted by the amount of available biomass and economically restricted by the cost of delivered biomass to the plant. This stresses the need for a reliable and cost-efficient supply of forest biomass.

Forest biomass parameters that affect the technical and economic feasibility of using it are its quality attributes, its availability and procurement cost. Biomass quality attributes are energy content, moisture content, particle size, ash and contaminant contents [5,22–24]. These attributes influence the selection of pre-processing operations (e.g. sorting, chipping, and drying), the selection of conversion technologies, the conversion yields, and the transportation costs. The amount of biomass that can be sustainably procured determines the scale of the project, and the variation of biomass supply over time drives the need for storage operations to ensure a reliable supply over the life time of the project. Biomass procurement costs include all the costs associated with collecting, storing, pre-processing and transporting biomass from its source to the plant.

Another important factor affecting the economics of forest biomass utilization to generate valuable products includes product distribution costs. Heat and electricity are usually produced to satisfy domestic energy needs; however, in the case of biofuels and chemicals, distribution operations have to be planned. For example, in some countries, pipeline distribution is the most economical alternative for fuel distribution; however, chemical and physical properties of certain biofuels impede the use of the existing pipeline infrastructure [13], and train, barge or truck transportation has to be planned.

The combination of all these factors impacts the technical and economic success of a forest biomass utilization project. Efficient supply chain designs require decisions on feedstock (sources and types); storage, pre-processing and transportation (type, capacity and location); conversion technologies (type, capacity and location); products and markets (type of products, and location of markets); and material flows (of feedstock and products) within the supply chain. All these decisions are case-specific, and they must reflect the particularities of each supply chain context.

2.2. Environmental considerations

Some of the major environmental issues of forest biomass utilization are related to carbon balance and greenhouse gas emissions, particulate matters emissions, and the forest ecosystem health [18].

One of the main drivers for the intensified utilization of biomass to produce energy and other materials is its potential to reduce the environmental impacts of fossil fuels utilization. It has been recognized that the use of fossil fuels (e.g. oil, coal, and gas) has accelerated the emission of CO_2 into the atmosphere leading to an increased greenhouse effect that causes global warming and climate change [25]. In forest-rich countries, the use of forest biomass to offset the use of fossil fuels has the potential to reduce carbon emissions. Forest biomass is considered as a renewable, and low carbon energy (or carbon neutral) source because carbon released in to air during combustion is sequestered during trees growth [25]. It is assumed that carbon neutrality will be achieved in the long term, when the new tree generation has reached a harvestable size [26]. However, a complete carbon evaluation of forest biomass utilization projects should also consider non-biogenic carbon emissions that are due mainly to the consumption of fossil fuels for the production, harvesting, collection, handling, pre-processing and transportation of forest biomass and distribution of products [27].

In addition to carbon, other atmospheric pollutants such as non-carbon greenhouse gases and particulate matters are generated throughout the forest biomass supply chain. Life cycle approaches are useful to quantify all the emissions to air, water and land, and to estimate potential impacts on climate change, human health, ecosystem quality, and resources depletion [27].

An important ecological consideration in planning forest biomass projects is the role of forest biomass in maintaining the health of the forest ecosystem [18]. Forest biomass (dead wood and forestry residues) helps to sustain forest soil and site productivity, regulate water flows and maintain biodiversity [18]. Forest biomass fertilizes the forest soil with nutrients and sustains its acidity, thus maintaining forest productivity levels [28]. Forest biomass affects the soil's ability to hold and transfer water, thus determining water quality, movement and distribution patterns in the forest [29]. Also, forest biomass provides shelter and food to various forest organisms [29]. Therefore, forest biomass removal

might have some negative effects such as reducing forest productivity levels, changing water downstream flows, affecting deadwood-requiring species, and increasing forest access that favor the spread of invasive species [30]. There are also some potential positive effects such as reducing the proliferation of pests' species [30], and reducing the risk of wildfires that disrupt biodiversity patterns [18]. In this regard, a large number of research efforts have been devoted to assess the impact of removing forest biomass from harvested areas, develop operational guidelines for forest biomass removal [29,30], and develop strategies to mitigate the removal of organic matter from forest areas [31].

Many strategies can be applied to improve the environmental performance of bioenergy and bioproducts production that use forest biomass. For example, the design of conversion facilities that integrate emission control equipment, water treatment processes, waste management and recycling can reduce the emission of pollutants to air, water and land. The use of highly efficient technologies along the supply chain reduces the amount of fossil fuel required for biomass collection, handling and transportation. The location of conversion plants close to large sources of biomass (e.g. forest-products mills) and to markets reduces the amount of fossil fuel required to transport biomass and products [30]. Understanding the environmental impacts of different supply chain choices is the key to ensure that the environmental benefits of using forest biomass are maximized.

2.3. Social considerations

The establishment of new forest biomass utilization projects might have multiple social effects on forest-rich regions. These social effects might include changes in people's way of life, culture, community, political systems, environment, health, well-being, personal rights, property rights, and even fears and aspirations [32]. However, many of these effects cannot be consistently quantified. Social effects that are commonly used in optimization of forest biomass supply chains and can be quantified are job and income creation.

The quantity and quality of jobs created depend on strategic decisions in the design of the forest biomass supply chain. The overall number of created direct, indirect and induced jobs depends on the size of the project. Overall, larger projects generate more jobs. However, there are some trade-offs that have to be analyzed. The number of jobs created per unit of forest biomass used tends to decrease as economies of scale are achieved due to the use of more efficient logistics and production systems [18].

Along with job creation, the development of new forest biomass projects generates income and development opportunities to rural communities [33] that could be translated into improved well-being for the population. Studies evaluating the potential social impact of these projects should analyze how the income will be allocated (if it will stay in the community or not). In addition, the generation of energy from forest biomass has the potential to increase the energy security of communities. This aspect could be analyzed and measured [34].

Furthermore, the supply chain has to be planned to address other communities' concerns regarding distance of plants to residential areas, protected areas, airports, wetlands and lakes, and critical environmental areas [35].

3. Assessment of forest biomass supply chains

In order to make sound decisions in the design and planning of forest biomass supply chains for bioenergy and bioproducts, decision makers need to envision the viable alternatives, and evaluate their potential economic performance, and impacts on the environment and the society. Assessment studies help in evaluating or predicting the performance of a project from different lenses. In the literature, most of the assessment papers (50 out of 54) considered a single evaluation factor, using either economic or environmental assessment tools. Only four studies documented the assessment of forest biomass supply chains evaluating social, economic and environmental indicators simultaneously. Fig. 2 depicts the classification of the studies on economic, environmental and social assessment of forest biomass supply chains, indicating their classification and purpose.

3.1. Economic assessments

In the literature related to the economic assessment of forest biomass supply chains, techno-economic analyses have been conducted to appraise the economics of different projects and evaluate the economic impact of various technical choices. Based on the purpose of the study, different assumptions, hypotheses, methods and metrics have been employed. Various techno-economic studies had the purpose of evaluating the economic feasibility of using the forest biomass generated by traditional

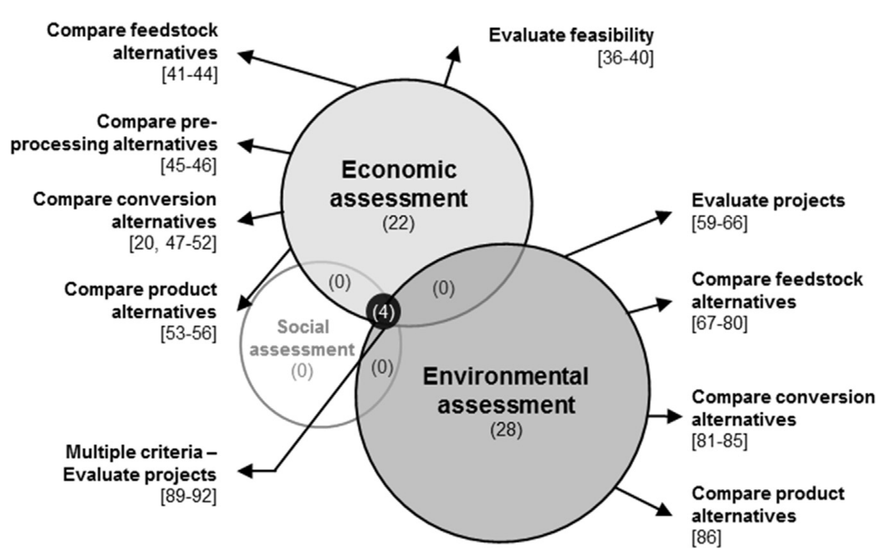

Fig. 2. Classification of assessment studies of forest biomass supply chains. The number of studies in each category is indicated in parenthesis.

forestry operations or by natural disturbances for the production of a particular type of energy or bioproduct (e.g. intermediate woody products [36,37]; electricity [38,39]; and biohydrogen [40]). Some other studies aimed at comparing among different feedstock alternatives [41–44], pre-processing technologies [45,46], conversion technologies [20,47–49], facility locations [50–52], or product alternatives [53–56] in the configuration of a supply chain. The most common economic metrics in this group of studies were levelized production cost and internal rate of return. Table 1 presents a summary of the papers reporting techno-economic studies of forest biomass supply chains.

Techno-economic assessments are required to investigate the technical feasibility and economic potential of proposed projects, and provide baseline economic comparisons among different choices in the forest biomass supply chain. They provide sound information and analysis to justify projects involving large capital investments, and aid specific decisions along the supply chain. However, techno-economic studies do not identify the optimal design of forest biomass supply chains. In addition, techno-economic assessments of forest-based bioenergy and bioproducts supply chains rely on average procurement and logistics data (e.g. average transportation and biomass costs), which neglects relevant factors in forest biomass supply chains including the geographical dispersion of forest biomass sources and the temporal variation of parameters such as forest biomass supply seasonality, and changes in production conditions (e.g. energy prices, efficiency improvements, etc).

3.2. Environmental assessments

Life cycle assessment (LCA) is the preferred tool to evaluate the environmental impacts of products throughout life cycle stages. LCA is a methodology for holistic and systematic evaluation of the environmental loads and the potential impacts of a product, process or service from its cradle (raw material extraction) to its grave (disposal) [57]. Principles, guidelines and components of LCA studies are described by the International Standards Organization series of standards ISO/EN 14040 [58]. These standards provide transparency and consistency in LCA studies. Based on these standards, the stages of an LCA study are (1) a clear definition of

Table 1
Summary of economic feasibility studies of forest biomass supply chains.

Purpose	Reference	Region	Case
Evaluate feasibility	[36]	Chile	Feasibility of wood chips production from pine harvesting residues using a mobile tree chipping machine
	[37]	USA	Feasibility of torrefied wood pellets production from round wood
	[38]	Canada	Feasibility of power generation from mountain pine beetle killed timber
	[39]	–	Feasibility of co-firing of forest residues in coal boilers for power generation
	[40]	Canada	Feasibility of hydrogen production from whole-tree forest biomass
Compare feedstock alternatives	[41]	Canada	Identification of biomass feedstock for different process configurations of biorefineries *Alternatives*: hardwood, forest residues and agricultural residues for the production of ethanol, bio-oil and syngas
	[42]	USA	Selection of biomass feedstock for ethanol production *Alternatives*: switch grass, hybrid poplar, corn stover or aspen wood
	[43]	Canada	Selection of biomass feedstock for hydrogen production *Alternatives*: whole tree biomass, forest residues, straw
	[44]	Australia	Selection of biomass feedstock and amount for co-firing with coal *Alternatives*: wood chips, wood pellets, torrefied pellets, black coal
Compare pre-processing alternatives	[45]	Brazil–Netherlands	Compared pre-processing technologies for cost reduction of international logistics of energy crops *Alternatives*: torrefaction, fast pyrolysis and pelletization
	[46]	–	Compared pre-processing technologies for cost reduction of delivered forest residue *Alternatives*: chipping, mobile fast pyrolysis, mobile torrefaction
Compare conversion alternatives	[20]	–	Compared technologies for power generation from agricultural and wood waste *Alternatives*: combustion and gasification technologies
	[47]	Europe	Compared technologies for power generation from short rotation coppice and conventional forestry *Alternatives*: pyrolysis, gasification, integrated gasification combined cycle and combustion
	[48]	–	Compared technologies for power generation from wood chips *Alternatives*: pyrolysis, combustion and gasification technologies
	[49]	UK	Compared technologies for large-scale power generation from forest biomass *Alternatives*: 350 MW-CFBC[a], 44 MW-BFBC[b] and 35 MW-BFBC
	[50]	USA	Facility location for ethanol production using softwood thinning *Alternatives*: stand-alone plant or co-location with biomass power facility
	[51]	Canada–Brazil	Facility location for ethanol production from woody biomass *Alternatives:* production in Ontario (poplar), New York (willow) and Brazil (eucalyptus)
	[52]	Serbia	Facility size and location for CHP[c] using wood-processing residues *Alternatives*: production in sawmills and pellet facilities
Compare product alternatives	[53]	USA	Selection of products from overstocked forest thinning *Alternatives*: wood pellets, bio-oil, methanol, power
	[54]	Canada	Selection of products from mountain pine beetle killed timber *Alternatives*: ethanol, bio-oil, power
	[55]	Canada	Selection of products from forest residues *Alternatives*: syngas, methanol, dimethyl ether, Fischer Tropsch liquid
	[56]	–	Selection of biofuel products from woody biomass *Alternatives*: synthetic natural gas, methanol, dimethyl ether, Fischer–Tropsch diesel, methanol-to-gasoline

[a] Circulating fluidised bed combustion.
[b] Bubbling fluidised bed combustion.
[c] Combined heat and power.

the purpose of the analysis, including its intended application, its scope, its limitations and assumptions, and the definition of a functional unit that constitutes the basis for comparison (goal and scope of the study); (2) the compilation of data related to materials inputs, energy inputs, waste outputs, emissions outputs assignable to the product (life cycle inventory LCI); (3) the categorization of potential impacts to the natural environment, to the availability of natural resources, and to the human health (life cycle impact assessment LCIA); and (4) the review and analysis of the calculations, as well as the discussion of results (interpretation). LCA has been widely utilized to analyze bioenergy, biofuels, and forest biomass systems with different purposes. In some studies, it was used to quantify and understand the environmental performance of a forest biomass project in a particular context [59–66]. In other studies, LCA was used to compare among different supply chain configuration alternatives. Murphy et al. [67] evaluated different forest residue removal strategies. A group of studies compared the environmental performance of different forest biomass feedstocks and/or other energy sources for heat generation [68–74], for power generation [75], for combined heat and power (CHP) [76–78], for the production of pellets [79], and for hydrogen [80], while others compared different conversion technology types and sizes for the production of an energy product [81–84]. Felder et al. [85] evaluated different forest biomass types and conversion alternatives. In these studies, the most common environmental impact investigated were global warming potential or greenhouse gasses emissions, followed by eutrophication, human toxicity and fossil energy consumption. Table 2 summarizes the studies using LCA to evaluate forest biomass supply chains.

LCA studies should not be used to provide the basis of comparative declarations of the overall environmental preferability of a product over another one [58]. The reason of this is that LCA results depend on methodological choices (e.g. scope definition, methods for impact evaluation, allocation procedures, and reference systems) and parameters associated with each analyzed case (e.g. local conditions) [87]. Nevertheless, LCA results have proved effective at understanding the environmental trade-offs throughout all the stages of the life cycle of a forest biomass utilization project, avoiding the shift of burdens resulted from partial environmental analyses during the design of the supply chain. Also, LCA results are useful to compare environmental impacts of alternative configurations of a specific forest biomass supply chain, provided that alternatives are evaluated under comparable modeling approaches and similar assumptions.

It is important to consider CO_2 sequestered by forests and wood over time in LCA studies. Meanwhile, standard LCA studies do not consider the impacts of forest biomass extraction on natural services (e.g. soil and water protection, and biodiversity conservation) that have high spatial and temporal impacts on the environment [88].

3.3. Social and multi-factor assessments

In the literature, even when many social indicators have been recommended to evaluate forest biomass supply chains, the type of indicators that have been quantified as part of socio-economic or multi-factor assessments are mostly related to the creation of employment opportunities. Some recent studies included quantifiable social factors in conjunction with other sustainability factors. First, Krajnc and Domac [89] introduced the SCORE model to estimate various aspects related to socio-economic and environmental impacts of a forest biomass supply chain. Their model considers qualitative and quantitative estimators such as contribution to forest management, impact on wood waste usage and other woody biomass usage, possible impact on regional unemployment, saved CO_2 emissions, avoided costs of unemployment and percentage of self-sufficiency in electricity production. Later, Päivinen et al. [90] proposed a module-based modeling method for assessing sustainability impacts in forestry supply chains. They demonstrated this approach by simultaneously evaluating the following three indicators: production cost, employment and CO_2 emissions. Finally, the Tool for Sustainability Impact Assessment (ToSIA) was presented by Werhahn-Mees et al. [91] and den Herder et al. [92]. ToSIA was developed by the EFORWOOD project in Europe to model, assess and compare bioenergy production chains. The indicators considered in ToSIA are production cost, resource/material use, total heat consumption at use stage, employment, wages and salaries, safety and health, GHG emissions, transport, energy use, soil quality, and carbon storage in cut biomass.

The quantitative evaluation of integrated social, environmental and economic aspects of forest biomass supply chains is a relatively new research area. Methods to evaluate social aspects of forest biomass supply chains have still to be developed. New methods have to evaluate the impact of new projects on human health, community well-being and ecosystems.

Economic, environmental and/or social assessment tools help in analyzing and comparing forest biomass supply chains from different perspectives. However, they are not able to recommend the optimal design of a forest biomass supply chain considering multiple decisions and multiple choices. This task can be supported by the use of mathematical programming or optimization [93].

4. Optimization of forest biomass supply chains

Mathematical programming is a useful tool for the selection of the best solution to maximize or minimize a quantitative objective considering scarce resources. An optimization problem is typically comprised of an objective function (linear or non-linear equation) expressed as a mathematical function of decision variables and other parameters that will be maximized or minimized according to the necessity of the problem, and a set of constrains (linear or non-linear inequalities or equations). In general, when the objective function and constrains are linear, the optimization formulation is a linear programming model (LP). When all the decision variables in a model have to be integer values, the model becomes an integer programming model (IP). When the model has continuous and integer variables, it is a mixed integer programming model (MIP).

In the literature, a number of optimization studies focused on supporting decisions in the design, planning and management of forest biomass supply chains. The majority of them (28 out of 35) pursued a single economic objective function. Recently, research efforts (7) were made to optimize multiple objectives that included economic performance, environmental impact and social impact metrics. Fig. 3 shows the classification of optimization studies of forest biomass supply chains.

4.1. Economic optimization

Economic optimization models have been developed to deal with a wide range of decisions at strategic and tactical planning levels of the forest biomass supply chain. Strategic models aim to address the long term planning decisions and allow for high level decision making. Tactical models deal with decisions for shorter periods usually less than a year. Table 3 shows the classification of studies and their major decisions. A large number of the problems studied were formulated as MIP models, and the most common

Table 2
Summary of LCA studies of forest biomass supply chains.

Purpose	Reference	Region	Case	Scope
Evaluate products	[59]	England	Three small scale heating systems using waste wood (for single building heating and district heating)	From waste collection to energy generation
	[60]	Japan	Use of municipal solid waste and waste wood to supply energy to a pellet manufacturing plant, and use of pellets for household energy	From fuel extraction in forest to energy generation
	[61]	USA	Wood pellets produced from hardwood flooring residues	From waste collection to energy generation
	[62]	USA	Production of wood chips as a feedstock for ethanol production	From silviculture to the gate of conversion plant
	[63]	USA	Future gasoline and diesel production from forest residues using fast pyrolysis	From fuel extraction in forest to energy generation
	[64]	Singapore	Bio-oil production through the fast pyrolysis of wood waste	From waste collection to energy generation
	[65]	Canada	Exploration of different rates of wood pellet co-firing with coal *Alternatives*: 100% wood fired, biomass co-firing with coal, natural gas	From fuel extraction in forest to energy generation
	[66]	USA	Evaluation of strategies for mitigating GHG emission in power production *Alternatives*: 20% co-firing with forest residues and woody crops vs. biologic and geologic sequestration of emissions	From fuel extraction in forest to energy generation
Compare feedstock alternatives	[67]	Ireland	Evaluation of forest residue removal and handling strategies *Alternatives*: thinning, bundling, stump harvesting	From silviculture to the gate of conversion plant
	[68]	Switzerland	Evaluation of energy feedstock for heat and transportation fuels *Alternatives for heat*: wood chips, woody SNG[a], fossil gas and oil; *Alternatives for transportation fuels*: SNG car, natural gas car and petrol/diesel car	From silviculture to energy generation
	[69]	Spain	Evaluation of biomass feedstock for heat production through gasification *Alternatives*: recycled wood, forest residues	From waste collection to energy generation
	[70]	Canada	Evaluation of energy feedstock for district heating *Alternatives*: wood pellets, natural gas, sewer and ground heat	From fuel extraction in forest to energy generation
	[71]	Canada	Replacement of a natural gas-based district heating system with a forest biomass system *Alternatives*: wood waste and forest harvesting residues, wood pellets, natural gas	From fuel extraction in forest to energy generation
	[72]	Europe	Evaluation of biomass feedstock for heat production through gasification *Alternatives*: forest residues, woody energy crops, natural gas	From fuel extraction in forest to energy generation
	[73]	Canada	Evaluation of energy feedstock for residential heating *Alternatives*: firewood, wood pellets	From fuel extraction in forest to energy generation
	[74]	USA	Evaluation of energy feedstock for the production of energy *Alternatives*: pyrolysis bio-oil from commercial pine thinning, residual fuel oil	From waste collection to energy generation
	[75]	USA	Evaluation of energy feedstock for power production *Alternatives*: solid biomass and pyrolysis bio-oil (from mill residue, forest residues or wood energy crops) and fossil fuels	From silviculture to energy generation
	[76]	Norway	Evaluation of biomass feedstock to substitute oil and coal for the production of heat and power *Alternatives*: fuel wood, sawdust, bark and demolition wood; pellets and briquettes; oil and coal	From fuel extraction in forest to energy generation
	[77]	Sweden	Evaluation of feedstock/process combination for bioenergy production *Alternatives*: waste incineration (paper, demolition wood, compost, etc.), combustion of wood fuel, natural gas	From waste collection to energy generation
	[78]	USA	Evaluation of feedstock type for production of heat and power at a softwood lumber mill *Alternatives*: mill and forest residues, wood pellets, natural gas	From waste collection to energy generation
	[79]	USA	Premium wood pellets production from wood processing co-products and whole logs	From silviculture to energy generation
	[80]	Spain	Evaluation of feedstocks for the production of hydrogen through gasification *Alternatives*: vine and almond pruning, forest waste from pine and eucalyptus plantation	From silviculture to bioproduct generation
Compare conversion alternatives	[81]	Norway	Evaluation of production process for ethanol production from woody biomass *Alternatives*: biochemical vs. thermochemical process (syngas production and synthesis)	From fuel extraction in forest to energy generation
	[82]	Turkey	Comparison of technologies for the production of bio-hydrogen from forest wood waste *Alternatives*: DG[b], CFBG[c]	From silviculture to energy generation
	[83]	Norway	Comparison between old and modern stoves for the production of household heating from birch wood	From silviculture to energy generation
	[84]	Norway	Evaluation of facility sizes c for combined heat and power plants to be fed by forest residues and sawmill residues *Alternatives*: micro (0.1 MWe), small (1 MWe) and medium (50 MWe)	From fuel extraction in forest to energy generation
	[85]	Finland	Evaluation of feedstock types and conversion options from different types of forest biomass *Alternatives*: harvesting residues, small-diameter energy wood, stumps; CHP[c], condensing power production, torrefied pellets, gasification and pyrolysis oil production	From fuel extraction in forest to energy generation
Compare product alternatives	[86]	Switzerland	Evaluation of SNG production from wood through gasification and methanation and comparison of SNG final applications against reference systems *Alternatives*: SNG for heat, power, transportation vs. fossil fuels for heat, electricity and transport and conventional wood based heating	From silviculture to energy generation

[a] Synthetic natural gas.
[b] Downdraft gasifier.
[c] Circulating fluidized bed gasifier.

objective was to minimize the total supply chain cost, and to a lesser extent, to maximize profit.

Mathematical programming and optimization models are particularly useful when different decisions at different supply chain stages are combined [3], and when multiple time periods are considered. An optimization model can be applied to various supply chains provided that assumptions are valid for all of them, and data are available. The development of solution algorithms and advances in computational hardware and software [126] permit the inclusion of a large number of parameters, decision variables and constraints in the mathematical programming models simultaneously, and provide optimal solutions in relation to a defined objective function. However, to ensure the tractability of the model, and to keep computational solution times within practical margins, practitioners have to strive for simplicity in models formulation [127].

In the literature reviewed, the majority of studies focused on strategic decisions to support the allocation of investment and the generation and analysis of policies in the forestry and energy sectors. There is a recent trend to develop tactical optimization models dealing with logistics, production planning and scheduling problems. The majority of models were deterministic, and some studies addressed the impact of changes in different parameters using sensitivity (e.g. [17,94,95]) or scenario analyses (e.g. [105,112]).

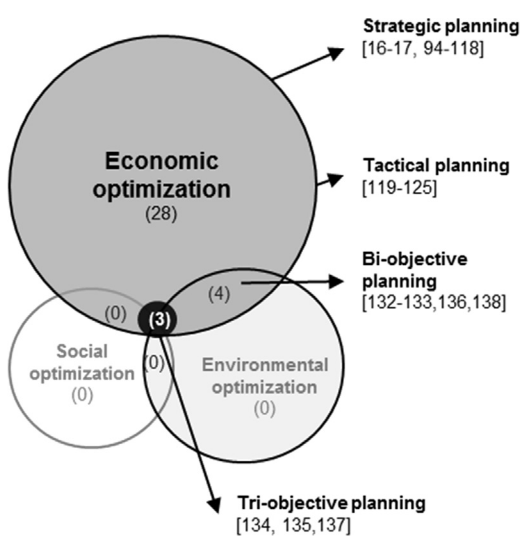

Fig. 3. Classification of optimization studies in the forest biomass supply chain. The number of studies in each category is indicated in parenthesis.

There are still opportunities to develop optimization models that integrate different planning levels, supply chain stages, and forest biomass products. It is noted that most published optimization models analyzed the supply chain from a multi-site organization's perspective, they assumed no conflict of interest between actors in the supply chain. While this might be the case for large integrated companies, it might not be proper for cases where each actor of the supply chain tries to optimize their own performance. The optimization of forest biomass supply chains considering negotiations among independent actors is an area still underdeveloped.

4.2. Economic, environmental and social optimization

The integration of economic, social and environmental objectives in the optimization of forest biomass supply chains for the production of bioenergy and bioproducts has been addressed in a few studies using multi-objective optimization (MOO) approaches. MOO is a sub-discipline within operations research that helps make choices characterized by multiple, non-commensurate and conflicting objectives [128]. In MOO problems, there is not a single solution that optimizes all objectives, instead there is a set (sometimes an infinite set) of “Pareto optimal solutions” [129]. Pareto optimal is a solution where one of the objectives cannot be improved without sacrificing another one.

In 1999, Azapagic proposed an approach for incorporating LCA into MOO for system optimization [130]. This approach has been used in some applications, mostly in process systems engineering [131]. The combined use of LCA and MOO to support decisions in forest biomass supply chains is a relatively new research area. To the best of the authors' knowledge, only seven supply chain MOO studies in the literature were related to the use of forest biomass which are the works of You and Wang [132], Santibañez-Aguilaer et al. [133], You et al. [134], Čuček et al. [135], Kanzian et al. [136], Sacchelli et al. [137] and Pérez-Fortes et al. [138]. Within this group, only You et al. [134] and Sacchelli et al. [137] integrated social objectives to the multi-objective optimization. Table 4 describes the main characteristics of these MOO models in terms of their optimization model, the criteria analyzed and the decisions addressed.

The most commonly used solution approach was the ε-constraint method [139] that produced Pareto optimal curves showing the potential trade-offs and compromises among them. Pareto frontiers allow the decision maker (planner) select the

Table 3
Major decisions addressed in forest biomass supply chain optimization papers.

Major decisions			**References**
Strategic	Feedstock decisions	Biomass feedstock source	[94,95]
		Biomass feedstock type and source	[96–98]
	Conversion facilities	Plant location and feedstock sources	*Single plant*: [99–101]
		Plant location	*Multiple plants*: [102,103]
			Single plant: [104–106]
		Plant location and size	*Multiple plants*: [17,98,107–109]
		Plant location, technology type and size	*Multiple plants*: [110–113]
		Technology type and size	[16,95,97,114–117]
	Products	Type and volume of products to generate	[94,104]
	Markets	Customers/markets to serve	[114]
	Flow of materials	Flows of biomass and products	[94,97,109,111,118]
Tactical	Biomass logistics	Location of storage and pre-processing terminals	[119]
		Flows of biomass through storage and pre-processing terminals	[120–122]
	Production planning and scheduling	Biomass procurement planning and scheduling	[123–125]
		Production planning	[125]

Table 4
Multi-objective optimization studies in the design of forest biomass supply chains.

Reference	Case	Model	Criteria			Decisions						
						Strategic					Tactical	
			Economic	Environmental	Social	F	T	C	L	P	IOT	SPT
[132]	Biofuels from multiple feedstocks	MIP	Annualized total cost	GHG emissions	–	x	x	x	x	x	x	
[133]		LP	Annualized profit	Overall impact (eco-indicator 99)	–	x	x			x		
[134]		MIP	Annualized total cost	GHG emissions	Accrued jobs	x	x	x	x	x	x	
[135]	Energy, food and boards from multiple feedstocks	MINLP	Profit	Non-renewable energy use, water use and pollution	Land use changes (relevant for energy crops)	x	x	x	x	x		
[136]	Bioenergy from forest biomass	MIP	Profit	CO_2 emissions	–						x	x
[137]		CP	Revenue	Avoided CO_2 emissions	Traffic annoyance	x	x		x			
[138]		MIP	NPV	Overall impact (impact 2002+)	–							x

Note: Abbreviations are as follows: LP: linear programming; MIP: mixed integer programming; MINLP: mixed integer nonlinear programming; CP: compromise programming; F: feedstock decisions; T: technology type; C: plant size; L: plant location; P: products; IOT: inventory size, production operations and transportation equipment selection; S: storage, pre-treatment and transportation decisions.

solution that best suits his/her preferences. However, this might not an easy task, especially when there are many decision makers involved. Multi-criteria decision methods such as Analytical Hierarchy Process (AHP), ELECTRE and PROMETHEE can be useful in this case [10].

The use of MOO approaches in the design of forest biomass supply chains for bioenergy and bioproducts has many benefits. They allow a better approximation to reality by including many factors that are important in the decision making process. However, assuring consistency in the formulation of the different objectives is challenging. For example, when combining LCA and MOO for the design forest biomass supply chains, analysts have to decide whether or not to consider environmental impacts associated with forest silviculture operations and harvesting, lumber production, products use and waste disposition (e.g. ash landfilling); or avoided emissions due to fuel substitution. These impacts are typically beyond the scope of economic analyses of forest biomass supply chains, but might have a significant effect in environmental terms.

5. Discussion

Considering potential economic, environmental and social implications of supply chain decisions is required to ensure the sustainable utilization of forest biomass for the production of bioenergy and biofuels. There have been different studies aimed at assessing and optimizing the design and management of forest biomass supply chains from different sustainability perspectives. The large majority of studies assessing forest biomass to energy and bioproducts production have examined the supply chain from an economical or environmental perspective. Techno-economic assessment studies have been useful to provide insights on the feasibility of biomass utilization under different geographical, regulatory, and market conditions. They have been useful to assess the economic feasibility of different forest biomass projects, and compare the economic performance of a small number of forest biomass supply chain alternatives. However, they cannot provide the optimum design of the forest biomass supply chain.

LCA studies can evaluate a wide range of environmental burdens and impacts throughout the life cycle of bioenergy and bioproducts. In many cases, LCA results cannot support declarations of overall environmental superiority of a forest biomass option over another one, but they help to develop environmental consciousness and recognize the environmental compromises among alternatives. For a complete environmental evaluation of forest biomass utilization, additional tools to LCA should be used to account for impacts on the health of forest ecosystems (soil, water and biodiversity).

Quantitative methods for social impact evaluation are scarce. A promising approach that could aid the assessment of social impacts of forest biomass utilization is the Social LCA framework; however, indicators and methods are still underdeveloped [140]. So far, only a limited number of studies quantitatively evaluated social impacts (mostly employment related) of forest biomass supply chains as a part of larger multi-criteria assessments. Assessment studies considering multiple factors provided a wider view of sustainability impacts of a forest biomass supply chain. However, they are not able to analyze the potential trade-offs among sustainability impacts, thus defaulting the ability to support holistic sustainability comparisons.

Optimization studies are useful in determining the optimum design of forest biomass supply chains when multiple alternatives exist along different stages and planning levels. Since the demand for bioenergy and bioproducts is expected to grow in the future [141], governments, investors and plant managers will require decision support tools to help them make the most efficient use of available resources. Former optimization efforts dealing with forest biomass supply chains were mainly focused on strategic decisions, but there is a recent growing set of studies dealing with tactical decisions. Optimization models alone will not be enough to support decision making. Models have to be embedded in practical and robust decision support systems if the intention is to support decision making [142]. These decision support systems should also consider environmental and social aspects to ensure sustainability of new forest biomass utilization projects.

The literature on modeling the environmental and economic aspects of forest biomass supply chains through combined LCA and multi-objective optimization approaches has started to flourish. This new approach has been efficient to integrate different sustainability criteria in the design of forest biomass supply chains. They can provide reliable information about sustainability trade-offs provided consistency in the units and scopes of different objectives. Nonetheless, social aspects have not been given the needed attention by this recent group of studies.

The main drivers for bioenergy and products generation from forest biomass are related to their potential to generate economic benefits; contribute to reduce environmental impacts associated with fossil fuels combustion; help communities diversify their energy sources and achieve energy independency; support rural

development; and increase sustainability. Further research is needed to study and quantify relevant social impacts of forest biomass utilization systems. There is also a need to develop decision support systems that incorporate environmental issues such as impacts on forest biomass carbon balances, biodiversity, forest resilience, and social issues such as community well-being in forest biomass supply chain design and planning.

6. Conclusion

Forest biomass has the potential to substitute fossil fuels in the production of bioenergy and bioproducts. Many decisions have to be made when designing and planning the supply chain of forest biomass for the production of bioenergy and bioproducts. The decision making process requires integral evaluation and consideration of a variety of sustainability factors in order to ensure real benefits to the society and the economy, in a way that is less harmful to the environment.

Several studies measured and optimized economic, social and environmental performances of forest biomass supply chains. This paper presented a state-of-the-art review of assessment and optimization methods and their applications in forest biomass supply chains.

So far, the majority of studies had a partial view of forest biomass projects. Through techno-economic assessments and life cycle assessments, the economic and the environmental performance of different forest biomass supply chains have been evaluated, respectively. Economic optimization has been widely used to aid in the design of forest biomass supply chains. There is a need for decision support tools that quantify and optimize the economic, environmental and social aspects of the forest biomass supply chain simultaneously. This might involve the use of tools such as life cycle assessment, multi-objective optimization and the development of other tools to quantify sustainability impacts.

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